VOLUME 76 SEPARATE No. 7

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PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

MARCH, 1950

AMERICAN SOCIETY OF CIVIL ENGINEERS FOUNDED 1852

THE GEOCHEMISTRY OF EARTHWORK

By Hyde Forbes, M. ASCE

SOIL MECHANICS DIVISION

Headquarters of the Society
33 W. 39th St.
New York 18, N.Y.

PRICE $0.50 PER COPY

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Published at Prince and Lemon Streets, Lancaster, Pa., by the American Society of Civil Engineers. Editorial and General Offices at 33 West Thirty-ninth Street, New York 18, N. Y. Reprints from this publication may be made on condition that the full title of paper, name of author, page reference, and date of publication by the Society are given.

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Printed in the United States of America

AMERICAN SOCIETY OF CIVIL ENGINEERS
Founded November 5, 1852
PAPERS

THE GEOCHEMISTRY OF EARTHWORK

By Hyde Forbes,[1] M. ASCE

Synopsis

The geochemistry of earthwork involves the geologic and chemical processes that account for the kinds and quantities of mineral substances found in earth that has been "worked" in the presence of air and water. It should be advantageous for engineers and technicians concerned with earthwork to follow these geochemical processes and products, as well as the mechanical properties assumed by earth, in order that a complete and effective technique may be developed in the entire field of earthwork. This paper presents observational and test data relative to the geochemical processes and the mineralogical change set up in working with earth in excavations for engineering structures.

A comparison is drawn between the natural processes of rock weathering, erosion, and deposition as observed by all, and as encountered in engineering construction. It is common knowledge that the rock-forming minerals making up the earth's crust are compounds of the elements and, although it is not necessary that the engineer know the infinite number of possible chemical combinations of the elements that have been effected, he should recognize the fact that compounds are being formed continuously (under natural conditions and agencies) which are important in connection with unyielding foundations and stability of slopes. Compounds may be affected by the union of elements during the mechanical processes involved in earthwork, the character of the product of such unions being important in the final production of stable, dense structures.

Those who select construction material and control its use in construction should consider its mineral content in order to obtain material which, when worked with air and water, will result in dense, relatively impervious, stable masses. Material that will react unfavorably with water and atmospheric gasses should be avoided. Similarly, excavated slopes and faces in natural material should be considered in the light of the following: (1) The mineral

Note.—Written comments are invited for publication; the last discussion should be submitted by August 1, 1950.

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character and structure of the excavated material; (2) its future action in contact with the atmosphere and moisture; and (3) the effects produced upon structures built in or adjacent to the excavated areas as the foundation soil becomes modified by geochemical change.

Introduction

Since the late 1920's the application of scientific investigation to natural materials and to construction design and control in earthwork has produced much literature relative to physical and mechanical properties. However, there are fundamental geologic phenomena involved which would appear to be of primary interest to the geologist and which have been generally neglected. These include the definition of the mineralogical characteristics of the materials, the geochemical reactions they undergo upon excavation, and the changes that occur with handling, moistening, and compacting to produce general stability of foundations and slopes in earth structures. The vagaries of nature are legion and often unpredictable except from a rather broad point of view. The products of geochemical action in earthwork may vary greatly even under similar conditions of moisture and working. What little is known positively, conclusively, and completely is that the earth's crust and its constituents are subject to constant change. The accumulation of observational and test data during the working of earth, and after the completion of that work, should prove extremely valuable.

Materials encountered in earthwork are all products of rock. The reactions that occurred during the formation of rock resulted in a chemical equilibrium. The chemical system is one in which changes occur by the interaction of various natural agencies, resulting in the formation of a new set of combinations of mineral species recognized as the products of rock weathering and decomposition. The latter (weathered and decomposed rock), in turn, become stable for existing conditions or are subject to further change or decay. These species are the result of the chemistry of nature; but in earthwork construction the process may be continued and other compounds generated artificially in the reworking of these species as secondary units of geochemistry.

The formation of the secondary units is the result of relatively simple reactions. The principal agencies are atmospheric gases and water, both of which are intensely active in construction processes. Rock (or a rock-forming mineral with its associations) is the result of chemical change. It is subject to further change or transformation into other forms of mineral matter (under certain conditions) during a period of time dependent on those conditions and on the rock-forming minerals involved. The products of these changes (in the case of soil, for example), under proper conditions, are subject to reconsolidation to a degree dependent upon time, pressure, and association with other elements or compounds of elements. To summarize: This cycle of change is the result of the physical, mineralogical, and chemical constitution of matter; and the physical, mineralogical, and chemical changes possible within that constitution, under certain conditions, compose the geochemistry of earthwork.

Weathering, a Geochemical Change Through Geologic Processes

The results of weathering as a geological process are important to the engineer engaged in foundation excavation; and the construction procedure parallels, facilitaties, and accelerates the geologic process. Igneous rock originated as molten fluid in which the elements occur mutually dissolved under intense heat and pressure, the reduction of which allowed the elements to combine to form cohesive crystalline aggregates of distinct rock-forming minerals in chemical equilibrium. Crystalline metamorphic rock resulted from the formation of chemical combinations of elements present or injected under conditions of pressure or heat or both. Sedimentary rock is caused by the reconsolidation of the products of disintegration and decomposition of other rock through pressure, or the injection of other mineral matter (or both). Rock undergoes a gradual disintegration because each constituent mineral crystal has a distinctive coefficient of expansion and contraction, and the rock fabric is broken physically by temperature change between night and day, and the seasons. The partly disintegrated mass is then subjected to partial decomposition when attacked by atmospheric gasses and dissolved by rain or percolating water. Solubles are formed and carried away and others may be reabsorbed or deposited; and the remaining material, some in hydrated form, contains products subject to transportation by moving water or to further development into soil. This process is the well understood rock weathering—disintegration, decomposition, solution, and hydration—resulting in residual soils, in place, over parent rock and quarriable soft rock. Through erosion, transportation, and deposition, the product of rock weathering forms the alluvial accumulations of valley slopes and fills.

The readiness and rapidity with which geochemical change takes place in fresh rock surfaces were brought to the attention of the writer in 1915 in observing the foundation rock for the Gibralter Dam on the Santa Ynez River in California. The dam site consisted of a thoroughly cemented, massive sandstone containing abundant fossil shells. The shells had provided the lime which percolating water (having absorbed carbon dioxide) dissolved and redeposited as the mineral calcite in all interstices and joint openings. The site was stripped to fresh, sound rock and hosed off before pouring concrete; but overnight it slaked and the surface became covered with rock flakes, sand, and white, chalk-like dust. This loose matter was cleared with wire brushes, and again the detritus formed before concrete was poured. The question arose as to the effect which such action would have on the bond between the rock and concrete, and a chemical analysis was made. The reaction was simple—calcium carbonate, cementing material, exposed to the air, separated into its component parts, gaseous carbon dioxide and earthy lime. Some of the detritus was then molded with a small quantity of water lying in a pot hole in the bedrock, and allowed to dry in free air. The result was "rock hardness," which is said to be a reversal of the first action—that is, lime water plus carbonated water caused the carbonate to become visible to the eye as the water evaporated.

The weathering of fresh cut slopes and the rate at which the slopes deterio-

rated to result in landslides has been described by the writer elsewhere.[2] Tl same reaction has been observed in tunnels and other excavation varying i rapidity according to the mineral constituents of the rock. Blasting wa required in driving a tunnel in solid igneous rock under Parker Avenue in Sa Francisco, Calif., in 1939. However, the rock was attacked by the water vapo in the air, causing it to hydrate so rapidly that it was possible to scrape "clay from the tunnel roof and walls. The tunnel required lining. The variatio in the extent to which natural agencies attacked rock of varying miner composition was evident in the geological surveys and investigations made i connection with nearly one hundred proposed dam sites in California an Arizona. Each dam site presented distinctive geologic conditions and miner compositions in relation to the activity of geochemical change taking place, a evidenced by the quantity or scarcity of alteration products in the detrit cover, and the mineralogical character of the secondary products in the re siduum. The end result of the geochemical change in the weathering proce was the development of soil. Rock disintegrated to fragments; fragments wer broken up to particle size; and the crystalloid particles were changed to amor phous substances and colloidal particles. The process was one of continuin decrease in grain size.

Geochemical Change Accompanying the Handling of Earth

The geochemical processes of nature—oxidation and reduction, hydratio and dehydration, and solution and consolidation—are duplicated or continue by the methods of engineering construction. All such action and reaction begi when a deposit of natural material is first disturbed and continue throughou

TABLE 1.—Average Results of Gradation Tests Under Varying Conditions; Felt Lake Dam, Stanford University, Calif.

(Percentage of Grain Distribution by Weight)

Pit No.	Material	Larger than 1.0 Mm			1.00 Mm to 0.074 Mm			Silt and Clay		
		A	B	C	A	B	C	A	B	C
(1)	(2)	(3)	(4)	(5)	(3)	(4)	(5)	(3)	(4)	(5)
Type (a) Hill of Clayey Sandstone (Soil, Subsoil, and Disintegrated Rock)										
1	Soil and rock fragments over clayey sandstone	16	15	13	63	61	55	21	24	32
7		42	39	34	40	41	40	18	20	26
9		41	38	32	42	41	36	17	22	32
Type (b) Hill Capped by a Fresh-Water Deposit, Indicating a Lake Bed										
4	Soil and gravel of lake beds	48	46	40	39	39	36	13	15	24
8		62	62	53	26	24	20	12	14	27

the construction period, the degree of change and the resultant product being dependent upon the mineralogical character of the material at the site. Oxidation is most effective on surfaces exposed to the air, but both oxidation and

[2] *Transactions*, ASCE, Vol. 112, 1947, p. 393.

carbonization (as in the kaolinization of feldspars when carbon dioxide is absorbed) may extend beneath the surface. All processes are intensely active in, and with, material encountered in construction. Solution and hydration (through absorption of moisture as vapor or water) are accelerated, and the cycle of mineralogical and chemical change within the system continues until a final geochemical equilibrium is achieved under new conditions.

Felt Lake Dam (in California) *Construction Material.*—Reduction of the grain size, and change in the character of the borrow-pit material with handling, were noted during a check study on available construction material for Felt Lake Dam at Stanford University, in California, in 1929. Two types of materials were available (see Table 1): (*a*) Soil, subsoil, and disintegrated rock from a hill of

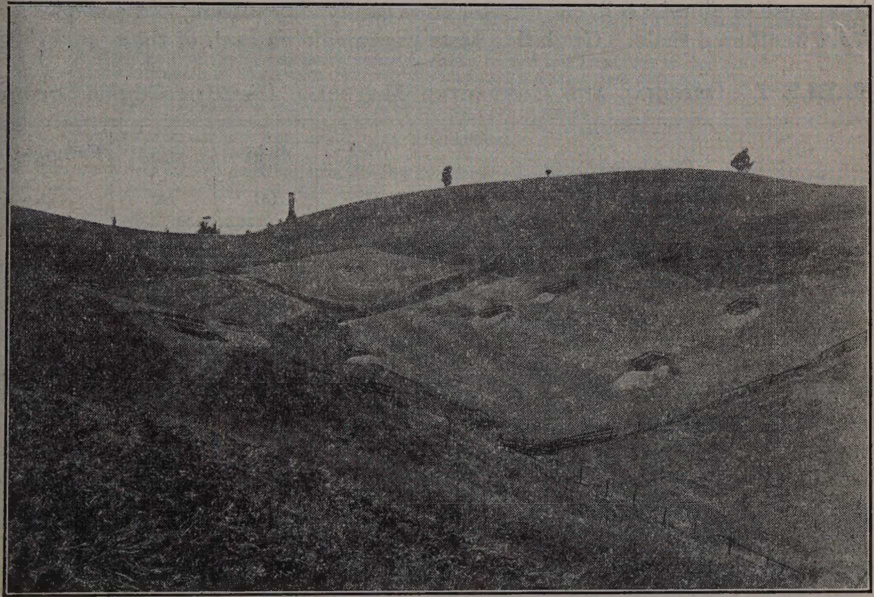

Fig. 1.—Swanzy Dam Site, North of Carquinez Straits, near Vallejo, Calif., Showing the Exploration Test Pits of 1929

clayey sandstone and (*b*) a hill capped by a fresh-water deposit presumed to be a lake bed. Pit 1 was shallow, principally soil, with few rock fragments. Pits 7 and 9 included the top of the disintegrated sandstone. Pits 4 and 8 (type (*b*), Table 1) contained gravel and boulders of the lake bed deposit. In Table 1 the results of the pit sampling are averaged to eliminate local differences. Cols. 4 contain the original screen analysis. As each pit was being dug, an average of three samples was taken and washed—the fines thus being separated from the coarse material, and dried in an electric oven. The lines were broken up with a wooden roller, mixed with the coarse material, and put through a set of standard screens. Samples A represent a later check with fresh samples cut from the wall of each pit through its entire depth (3 ft to 8 ft), broken by hand on the screens in an air-dried condition, and with shaking. The con-

sistently larger size found led to another check (samples C, Table 1) with representative samples quartered from the dump at each pit after being stacked in loose piles for some time. The increase in percentages of the fine particles was found to occur with the increase in handling and exposure to air and moisture.

Swanzy Earth Dam (in California) *Construction Material*.—Tests were made in 1929 and 1930 in connection with the design for Swanzy Dam, later incorporated into the water supply system of Vallejo, Calif. The limitations set by the capacity of the reservoir required on a pipe line from a well field and by the topography (see Fig. 1) made it necessary to construct the embankment of material excavated from within the site, using jointed shale. Surveys and test pits showed that approximately one half the required quantity could be obtained from wash or alluvial soil, one quarter from sandy clay subsoil, and one quarter from weathered shale. Gradation tests were made on each of these materials

TABLE 2.—ORIGINAL AND COMPACTED MATERIAL USED IN CONSTRUCTION

Description (1)	Wash soil (2)	Sub-soil (3)	Shale (4)	Compacted mix (5)
(a) Gradation; Percentages by Weight, Passing Each Sieve				
Size of Mesh:				
1.954	97.7	98.4	85.0	96.5
0.864	84.1	90.8	55.0	81.8
0.503	73.0	84.3	45.1	75.0
0.381	65.5	78.5	40.6	72.2
0.279	58.7	75.4	39.0	71.0
0.173	45.5	63.0	33.2	66.6
0.140	41.7	59.0	32.3	65.7
0.074	35.0	50.6	28.3	63.3
(b) Physical Characteristics				
Solubles in water, percentages by weight	0.3	0.4	0.2	0.2
Solubles in water with 5% HCl, percentages by weight	4.0	5.1	6.5	8.5
Dry density, in pounds per cubic foot	98.9	100.0	132.0	127.5
Moisture, percentages by weight	15.9	19.4	15.5	20.4
Approximate voids, percentages by volume	48.0	45.0	35.0	....

taken from the pits in the proposed borrow area, a typical example being shown in Cols. 2, 3, and 4, Table 2. Preliminary compaction tests were made with materials mixed in the $\frac{1}{2}$ to $\frac{1}{4}$ to $\frac{1}{4}$ proportions in a 4-in. cylinder. The shale content made it difficult to obtain complete compaction in the small cylinder. To approximate field conditions more closely, larger quantities of material were mixed and sprinkled on canvas and spread in layers in a steel box, 4 ft by 4 ft by 2 ft. A steel plate, 9 in. by 9 in., was fitted to a 4-ft handle, the whole weighing 25 lb; and this tamper was given an average drop of 18 in., until a thickness of about 9 in. of material was built up. Samples were cut from the center of the compacted material by a steel pipe with a cutting edge, 12 in. in inside diameter, having a capacity of 0.5 cu ft. These cut samples were used for density determinations and permeability tests, and smaller samples were taken for moisture determinations and sizing tests. The result of one such

test on the compacted material (at an optimum moisture-density relation), in comparison with those on the original materials as obtained from the pits, is shown in Col. 5, Table 2.

Conn Valley Earth Dam in California.—Determinations made in connection with construction (that is, a comparison of the results of sizing tests made on borrow-pit material with those made on samples cut from the compacted fill) have not been entirely successful. Because borrow-pit test holes covered only a small proportion of the actual borrow area their value as representative examples of that area was to be questioned. Table 3 gives the results of an

TABLE 3.—COMPARISON OF MATERIALS SAMPLED AND MATERIALS IN THE DAM, CONN VALLEY BORROW PIT, NAPA, CALIF.

Column Headings
Col. 1.—Average grading of the composite samples, taken from 6 test boreholes in area A;
Col. 2.—Average grading of 58 samples cut from the fill rolled material from area A;
Col. 3.—Boring samples, area B;
Col. 4.—Average of 115 samples from area B after compaction in the fill;
Col. 5.—Boring samples, area C;
Col. 6.—Average of 92 samples from area C after compaction;
Col. 7.—Boring samples, area D; and
Col. 8.—Average of 16 samples from area D, after compaction in the pervious section of the dam.

Description	Area A		Area B		Area C		Area D	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(a) Gradation; Percentages by Weight								
Gravel	21.6	16.9	0.5	14.2[a]	4.0	2.2	61.9	66.9[a]
Sand	42.2	29.8	49.0	22.2	47.1	13.8	30.0	24.7
Silt and clay	32.2	53.3	50.5	61.6	48.9	82.9	8.1	8.3
(b) Physical Characteristics								
Specific gravity	2.574	2.686	2.462	2.621	2.446	2.613	2.707	2.671
Approximate voids[b]	....	35.8	....	36.8	....	38.5	....	18.4
Moisture content[c]	....	13.9	....	17.2	....	19.3	....	6.4
Density, in pounds per cubic foot	....	120.3	....	121.0	....	119.4	....	144.8

[a] Material from the borrow pits was excavated deeper into the underlying gravel beds than the test boring in three cases. [b] Percentages by volume. [c] Percentages by weight.

effort to determine the physical change due to geochemical development during the construction of the Conn Valley Dam[3] by the City of Napa, Calif., in 1945. The construction material was taken from the valley fill and alluvium of Conn Creek in four borrow areas, designated A, B, C, and D. Gravel consisted of all rock material larger than the ¼-in. mesh; sand was material, large enough to pass the ¼-in. sieve and held on the 0.074-mm screen; and silt and clay was that material passing the 0.074-mm screen.

Many earth structures in California have utilized (wholly or in part) soft rock broken to fragmental form during excavation, and the fragments decompose with further working. The St. Mary's Playground fill in San Francisco was made by excavating jointed and weathered sandstone by pick and shovel,

[3] *Western Construction News*, January, 1945, p. 98.

dumping it loosely, and allowing it to settle. About ten years later more than 100 boreholes of 30 in. in diameter were drilled through the fill[4] allowing visual observation. All holes were found to penetrate a uniformly compact, relatively impervious, sandy, clay fill in which all semblance of the original fragmental character of the rock fill had disappeared, because of the kaolinization of the feldspar of the rock and the formation of amorphous, hydrous compounds from the original iron oxides with rainfall penetration. These observations and tests are not conclusive in themselves, but they substantiate geologic reasoning. It has been found that, in general, the physical composition or grain size of the material is of less significance than the mineral constituents.

Fragments, grains, and particles are minerals or groups of minerals, subject to physical distintegration and decrease in grain size in the process of working or shortly thereafter. Alteration of the mineral compounds to other forms of mineral matter through oxidation and reduction, hydration, and dehydration, and loss of gaseous components follows disturbance due to handling or exposure to the atmosphere. Reaction occurs when the same material is worked with water, producing new mineral compounds, apparently of still finer particle component. It is found that, with the decrease or reduction of the average grain size, all tested physical properties of a soil are changed. The size ratio of one particle to another, and the composition of the mineral compounds of silicon, iron, magnesium, and aluminum in a soil, have been found related to the cohesion of the soil and to its plasticity. The character of the mineral colloids present is the controlling factor in the capacity of the soil to absorb water physically. Hydration and solution are effected. Base exchange takes place when the soil is rendered plastic and is kneaded in compaction, as ions are adsorbed from the water, and thus produces new mineral forms. In a number of tests the geochemical change was demonstrated by the alteration in the specific gravity of the particles, as a result of handling. With the attack of atmospheric gases on freshly excavated material the reduction of particle size is explained, largely, in the production of oxides, hydroxides, and carbonates which are important in the geochemical changes effected through water.

Water

The most widespread evidence of geochemical change in natural materials is the effect of water in producing erosion and deposition. The transportation and accumulation of material by, and in, water facilitates the action. The principal agent that is active is water, through its oxidizing and solvent power. Table 4 is an example of the alteration which occurs when the mineral constituents of average types of matter are changing from crystalline rock to sedimentary rock. (The United States Geological Survey issues data on geochemistry.)

Similar results are caused by water in the transition of rock to residuum or soil over hillsides and, therefore, over excavated surfaces. Field observation and analysis show that water dissolves the more soluble minerals of the rock with the liberation of colloidal silica and with the formation of carbonates of lime, iron, magnesium, and the alkalies; oxygen reduces the ferrous compounds

[4] *Transactions*, ASCE, Vol. 112, 1947, p. 399.

to ferric compounds, sulfides change to sulfates, and carbonates of the bases are reduced to oxides. Carbonates are reformed with the absorption of carbon dioxide and they are generally abundant in residuum. The iron carbonate is oxidized to the rusty coating of silty ferric hydroxide. The alkaline salts remaining in solution in the soil water dissolve silica and cause the undissolved residues to hydrate, transforming feldspar to kaolin and magnesian minerals into talc; iron becomes essentially limonite. These hydrates make up clay, and

TABLE 4.—GEOCHEMICAL CHANGE FROM CRYSTALLINE ROCK TO SEDIMENTARY ROCK

Material	(a) PRIMARY MINERALS					(b) ALTERATION PRODUCTS			
	Quartz[a]	Feld-spars[b]	Ferro-magne-sian[b]	Mica	Acces-sory	Hy-drates[c]	Limo-nite[d]	Carbon ates[e]	Oxides
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Crystalline rock.	12.0	59.5	16.8	3.8	7.9	0.0	0.0	0.0	0.0
Sandstone.......	66.8	11.5	0.0	0.0	0.0	6.6	1.8	11.1	2.3
Shale...........	22.3	30.0	0.0	0.0	0.0	25.0	5.6	5.7	11.4

[a] In the form of free silica. [b] Unchanged. [c] Siliceous and aluminum hydrates. [d] Iron hydrate. [e] By the absorption of carbon dioxide.

the geochemcial change is accompanied by an increase in volume. Residuum supplies the greater quantity of material to be transported by rainfall runoff and streams, until deposited as alluvium. Alluvial deposits resemble sedimentary rock in composition, being a combination of sandstone and shale with a larger percentage of organic carbon and colloidal hydrates. The material of valley fills and slopes consists of the original rock eroded from the surrounding watershed, less a part removed through solution, plus oxygen, carbon dioxide, and water absorbed in the formation of new mineral matter, and the organic matter introduced through growths. The gains exceed the losses.

Effect of Water in Earth Fill Construction, Swanzy Dam.—That water had an important geochemical function in the construction procedure was also evident in the tests made on the material available for the Swanzy Dam in the fall of 1929. The bedrock consists of a series of stratified shale and subordinate sandstone beds. The latter contained fossil shells and had been cemented to an average specific gravity of 2.5 (156 lb per cu ft). An adequate water supply was not readily available at the dam site, and the ready access to sea water in near-by Carquinez Straits led to the consideration of its use for construction purposes. It was believed that, if the only function of moisture in compaction is to lubricate the material so that the grains would slide into firmer bearing under the compacting load, sea water would serve the purpose as well as fresh water. The materials (see Table 2) were sprinkled with sea water to make them somewhat plastic, but could only be compacted to a maximum density of 108 lb per cu ft. The compacted material proved to lack cohesion and, when air dried, it was loose and crumbly. When soil water from one of the pits was used in the compaction tests it was possible to obtain a density of 127 lb per cu ft and the air-dried samples were well consolidated. Chemical analysis

showed that the unstable bicarbonate in solution in the soil water formed normal carbonate when mixed with the calcareous material and worked. The compact material became cemented as the excess water evaporated. Sea water contains about 27.2 mg per liter of sodium chloride and but little carbon dioxide. The content of fairly unstable alkalies in the soil water aided in obtaining a hard, relatively impermeable material, whereas the use of sea water defeated this tendency through the reaction of the neutral and acid salts on the alkalies. Sea water made the material soft, as the absorption of calcium was limited and an insoluble binder was not precipitated in the interstices.

Water is the most active agent in the chemistry of nature and, apparently, in the geochemistry of earthwork. All minerals are attacked by water—some are attacked more intensely by water in which the alkalies are carried in alkaline or carbonated solution, and some react more strongly to acid solutions. All natural materials contain minerals which supply reagents in contact with water. The air transmits to water some of the most active reagents, such as gases and acids which are the products of organic decay, as well as carbon dioxide. The surface of soils and the soil cover contain humus and carbonaceous substances which are soluble in alkaline solutions. The solutions form humic acids, which are an important reagent in the production of siliceous hydrates and other colloidal substances. Any salt in solution will affect the solubility of a mineral in some manner, and soils (especially clayey soils) will absorb salts from water mixed with them or percolating through them.

TABLE 5.—AVERAGE RESULTS OF SOIL TESTS, TEST PIT AT FORT ORD RESERVOIR SITE IN CALIFORNIA

Depth below ground surface (ft)	Classification of sand	Weight, in place (lb per cu ft)	Moisture content[a]	Dry weight (lb)	Colloidal content[b] (% of weight)	Specific gravity of particles	Solubility in 5% HCl
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0– 2	Top soil not tested[c]	....	....	....	....	....	....
2– 4	Noncohesive sand	108.3	9.9	98.3	6.4	2.641	3.12
4– 6	Slightly cohesive sand	107.5	8.2	98.7	11.0	2.683	1.40
6– 8	Cohesive sand with silt lenses	108.5	7.8	100.7	14.5	2.700	1.41
8–10	Reddish, noncohesive sand	110.0	8.4	101.5	10.6	2.657	1.68
10–14	Noncohesive sand	108.0	9.2	98.7	7.0	2.623	2.36

[a] Percentage of dry weight. [b] By elutriation. [c] Roots and vegetation in loose sand.

Fort Ord Reservoir in California, Proposed as Balanced Cut and Fill.—The function of water in connection with construction and construction material is that it, first, produces substances from rock and soil with which it reacts to produce other substances. This behavior was apparent in testing dune sand in two instances. The first instance occurred in 1942 at the site of the Fort Ord Reservoir, less than 2 miles from the shores of Monterey Bay, California. A soil profile of the proposed cut area was made through borings, and a test pit was dug at a location that promised average characteristics of the material to be rolled into a fill and embankment. Equipment such as described in connection with the Swanzy Dam tests was used and samples, in place, of 0.5 cu ft were

cut from the bottom of the pit as it was being dug. The results appear in Table 5.

The silt was light colored and the sand contained only a small percentage of the rusty-colored iron hydroxide. Solubility tests showed an average loss of 0.2% in weight when a sample was agitated in water, and 2.20% was found to be soluble in a 5% solution of hydrochloric acid. The percentage of material that would react to form a "binder" when worked with water (thus increasing cohesion and stability) was small. The material from the test pit was given compaction tests following the procedure used on the Swanzy Dam. The maximum compacted density was 111 lb per cu ft (dry weight) achieved with a moisture content of 12.8%, by weight. Tests showed that the resultant material contained a slightly greater amount of soluble compounds (0.45% in water and 2.54% in a 5% solution of hydrochloric acid), with but little change in the average specific gravity of the particles. Compaction tests provided samples for quick shear tests made to determine the degree of cementation and consolidation. Cohesion was found to equal 575 lb per sq ft. Under given normal loads, the samples sheared with a horizontal pull (in pounds per square inch) of:

Normal load	Horizontal shear pull
11.1	12.8
27.8	26.1
76.0	55.5
117.0	95.9

The angle of friction of the compacted material was 38°.

A practical application of knowledge of the unsatisfactory constitution and behavoir of soils, obtained through observation and test, was made on this job. The dune sand at Fort Ord was constantly accumulating and had a sparse cover of brush and grass. The part to be excavated for the basin was largely unchanged through rainfall penetration. The induration of the material through the deposition or development of cohesive material was poor. The foundation fill and embankment to be located on a slope were subject to a fluctuating live load (maximum 1,500 lb per sq ft), and compaction was unsatisfactory. The compacted samples became unstable with moisture content in excess of 13% of their dry weight. There was little likelihood that the moisture could be controlled within the required limit during the winter months of February and March, 1942, when construction was required to meet the emergency program. There was no opportunity to select more favorable material without excessive haul. The writer reported that the sand to be excavated from the basin could not be consolidated sufficiently to provide the cohesion and resistance to shear required by the completed structure. Accordingly, the balanced cut-and-fill reservoir that had been planned was abandoned in favor of a pre-stressed concrete tank.

Sutro Forest Reservoir in California.—Material of the same origin and method of deposition on the west slope of Twin Peaks in San Francisco, however, had undergone such change as to be satisfactory—when used with other material to be excavated from within the site—for Sutro Forest Reservoir

constructed by the Water Department in 1945. A eucalyptus grove had been planted closely over the site many years previously. Rainfall on, and through, the forest litter dissolved that matter and became charged with humic and carbonic acids. The action of these solutions on the feldspars, quartz, and iron compounds making up the sand (producing clayey substances throughout the upper 10 ft to 20 ft of the deposit) could be seen in the walls of the pits. Borings (maximum depth 145 ft) to bedrock gave core samples that showed the effect of the change caused by the percolation of acid and ferruginous waters. A soil profile was developed from observations of auger borings and sampling on 100-ft centers to a depth dictated by the bottom of the cut, or by the occurrence of bedrock within the cut. Selectivity could be practiced because cut quantities exceeded those required for the fill and embankment.

Samples were classified as "good," "fair," and "poor," according to the percentage of secondary products contained, as evidenced by color. Materials of each classification, to certain depths below ground surface, were mixed with an excess of water, patted into molds without any attempt at compaction, and allowed to dry slowly in the moisture-laden air of a screen house. Portions of the air-dried samples were agitated in distilled water, filtered, air dried, and weighed; then they were agitated with a 5% solution of hydrochloric acid, filtered, dried, and weighed. Clay capped each sample in the filter after each water washing, increasing in thickness from "poor" to "good." The test for solubility in weak acid showed the fresher dune sand to have lost an average of 4% by weight; and lens examination showed that most of the black sand (ferromagnetite) grains were dissolved. The hydrous hematite and limonite of the red-brown clayey sand was less soluble. The average results of these preliminary tests are given in Table 6.

TABLE 6.—PRELIMINARY TESTS ON CONSTRUCTION MATERIAL, SUTRO FOREST RESERVOIR, SAN FRANCISCO, CALIF.

Average specific gravity of sand particles	2.593
Average weight of particles (pounds per cubic foot) in solid dry mass	161.7

Classification	Weight, air dried (lb per cu ft)	Density (%)	Voids (%)	Soluble in: Water	Soluble in: 5% solution HCl
Poor	101.6	62.3	37.7	0.11	4.00
Fair	111.9	69.2	30.8	0.30	2.80
Good	117.8	72.8	27.2	0.61	2.30

In the normal weathering process, the usual cycle of geochemical action caused by water is as follows:

(1) Partial solution of soluble matter with the liberation of colloidal silica;
(2) The formation of the carbonates of iron, lime, magnesium, and the alkalies;
(3) The solution of the lime, magnesia, and alkaline carbonates;
(4) The hydration of the iron carbonate forming ferric hydroxide; and
(5) The hydration of the undissolved residues to hydrous silicates.

Clayey or hydrated material is created by the chemical combination of water and minerals; dehydrated, it is physically capable of absorbing and retaining water and solutions. Not only is it desirable that geochemical action shall have taken place in the material to be used in construction, but also that further reaction take place when the water is mixed with the materials in the compaction process. Most water used in construction is from normal water supplies low in salinity or alkalinity. It usually contains bicarbonates of bases in solution; but with the absorption of carbon dioxide from the air the solvent power is increased. The bicarbonates are held in solution until evaporation produces concentration, when the normal salts are precipitated; or the alkaline solution forms soluble silicates and these have an affinity for water, hydrating and changing to amorphous substances, which are effective "binder" material. Nearly all natural material has some strong base present, giving the mixture with water an alkaline reaction. The result is an exchange of bases between the silicates of the material and the dissolved salts.

Compaction and Consolidation

The Sutro Forest dune sand had become more hydrous than that of Fort Ord because the constituent minerals, in place, had undergone a geochemical change. The materials had a lower average specific gravity, were more cohesive, and became plastic at a lower moisture content. Compacted in a somewhat plastic state a further geochemical change took place, the end result being a stable mineral material having a higher specific gravity, which becomes more or less consolidated, depending upon the character of the mineral "binder" developed. This action was found to take place in working the materials from the borrow pits into the Conn Valley Dam. (Compare the specific gravities noted in Table 3 except for the gravel of the pervious section.) It was also found to occur when tests were made in 1948 with borrow-pit material to be used for the impervious clay core of an embankment proposed for the Alameda County Water District near Niles, Calif.

Impervious Clay Core Material, Niles Embankment.—The clay used was that found existing as wash from rainfall erosion of hills, consisting of Cretaceous shale, a blue-gray, carbonaceous, fine-grained to sandy-textured rock. The disintegration and decomposition effected through weathering, transportation, and deposition produced a gritty clay, rusty brown in color (due to iron compounds). This clay contained silt and colloidal particles of several oxides and hydrates. It was friable when dry, crumbly and lumpy when damp, and plastic when moist to wet. The tested physical characteristics of 4 representative borrow-pit core samples (Nos. 1 to 4, inclusive) are given in Table 7 (see samples 1 to 4). Sample 5 is cut from compacted mixtures of the borrow-pit material, taken at a maximum compacted density or optimum moisture-density relation. The most striking change that occurred when the mixture was worked was in the color, the resultant being a dark, gray-brown, compact, impervious mass.

The fact that soils enter into chemical and mineralogical exchange with solutions, giving off some elements and taking up others, has long been utilized by irrigation engineers in soil treatment. The function of water or moisture in

embankment construction, and its effect in other engineering work, are of primary concern to civil engineers who are utilizing the geochemical and mineralogical changes which it produces in adapting natural materials to construction purposes. Engineers are faced with such changes in excavating, in tunneling,

TABLE 7.—COMPARATIVE TESTS ON CLAY BORROW-PIT MATERIAL, IN PLACE, AND AS COMPACTED; CLAY CORE FOR THE ALAMEDA COUNTY WATER DISTRICT EMBANKMENT, NILES, CALIF.

Sample No.	Density, as sampled (lb per cu ft)	Moisture content (percentage by weight)	Dry density (lb per cu ft)	Colloidal fraction by elutriation (%)	Specific gravity of particles	Lower plastic moisture content (percentage by weight)	Percentage Solubility in	
							Water	5% solution of HCl
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	101	14.3	88	32.0	2.780	15.4	6.0	3.0
2	106	9.8	96	32.0	2.820	16.5	4.0	4.0
3	112	13.8	99	30.0	2.840	17.1	5.0	3.5
4	110	11.6	98	29.0	2.800	15.5	6.0	4.0
5	144	16.1	124	20.0	2.930	16.5	3.0	20.0

and in foundations for structures. The geochemical action that accompanies disintegration of material with excavation, and the decomposition that takes place when the fragmental material is exposed to atmospheric gases and solutions, has received scant, if any, attention in the literature. The passage of the roller (especially the sheep's-foot roller) mixes and entraps moisture and air with the material so that it can do its work. The amount of water used and the fineness of particle resulting during construction are such that complete reactions never occur in the share that they do in the laboratory, where materials and water in chemical equivalents remain after excess water has evaporated. The moisture-density relation is important in that a degree of plasticity is required to facilitate and accelerate geochemical activity and achieve maximum density. It is apparent that such relation will change, within limits, because of the mineralogical and physical make-ups of the materials, possibly in the same borrow area.

The necessity of reducing the size of voids between particles, so that they can be consolidated in some degree through cementation, is obvious. The process of cementation begins as the chemical combination takes up moisture. In that process, the internal pressure that accompanies expansion holds the particles in place until induration is achieved. The induration may be entirely due to the action of the clay fraction. As the clay becomes less hydrous it tends to adhere to crystalline material; it becomes amorphous after the water taken up by the chemical system is "fixed" through evaporation, binding the coated particles together. The cementing may be caused by: (1) The solution of moist surfaces of minerals in contact with each other; (2) the base exchange in the presence of solution which forms amorphous film mineral binder; (3) the deposition of solubles from concentrated solutions; or (4) the combination of all these to increase the density of a given body of material. The hardpan and caliche lenses in alluvial deposits of the semiarid west are a common example

of cementation. Carbonates are carried in solution as the water containing normal carbonic ions transmits carbonic acid to the material with which it comes in contact. The bicarbonate ion loses its carbon dioxide through evaporation and the normal carbonate is precipitated in the interstices of the soil. The degree of mineralogical change with consolidation of worked material will be evidenced by the increase in the specific gravity of its constituents. The specific gravity or density of a solid depends upon the nature of the chemical substances of which it is composed and the state of its molecular aggregation. The density of hydrous minerals is low (2.3 to 2.5), but as the change takes place it will be nearer that of unchanged minerals (2.6 to 2.9). The specific gravity is an index of fundamental importance in identifying change in the hydrous character of construction material.

Gordon Valley Dam, in California.—Shale is a sedimentary rock made up of closely packed, fine particles, having a low permeability. Colloidal matter formed in conjunction with water from minerals of particle size is capable of binding granular or fragmental material under the influence of pressure alone, and such process in nature results in compaction shale. The same process under earth fill construction procedure produces a cohesive, dense mass. Such action was evidenced during the construction of the Gordon Valley Dam[5] for the City of Vallejo in 1925. Most of the structure was composed of the valley fill upstream from the dam site; but, at a certain stage, a dark, thin bedded, carbonaceous shale, excavated from the spillway and outlet tunnel, was rolled into the dam. The fresh shale was little altered in place; it slaked and oxidized quickly with handling; it broke down to a powdery, dry, light-colored dust on the construction road and formed a blue-black clay when sprinkled and rolled into the fill. That there was organic material in the shale was evident because the release of carbon dioxide gas in the short outlet tunnel made it difficult to keep a match lighted.

Notes made at the time show that, generally, the volume of the measured fill in place exceeded the borrow-pit measurement, but the swell of the shale portion was greater than that of the alluvium. The swell of the shale portion was probably more pronounced because the organic materials release great quantities of carbon dioxide which, with water, form acid reagents that dissolve the alkalies readily. There is a constant exchange of bases in solution, with a regeneration (precipitation) of carbonates in the compaction, and a consolidation of the structure. The similarity between the natural geologic processes responsible for the formation of the shale and those taking place during construction was impressive. The maximum degree of consolidation accompanies the following essential construction requirements:

(*a*) Adequate compaction with heavy unit loads to break fragments and to force grains into closer contact;

(*b*) Sufficient moisture to give all the material an initial plasticity, to encourage base exchange, and to assure an adequate absorption of solutions; and

(*c*) Thorough kneading by the repeated passage of the roller, in order to hold water and air in the soil long enough to do their work, and to expel the excess progressively as the consolidation process continues.

[5] *Western Construction News*, January 25, 1926, p. 15.

The writer has observed that, as shale or clayey material loses its carbon dioxide, it becomes lighter in color, the oxides of the alkaline bases are reformed through oxidation, and the carbonates are regenerated in compaction. The compounds of iron and aluminum and siliceous hydrates will increase tremendously in volume, exerting pressure if confined, because of the absorption of alkaline solutions. For example, the oxides of iron and aluminum, which are present in most material, can take up as much as 20 mols of water to 1 mol of oxide. Such action is frequently the cause of the failure of excavated slopes, retaining or basement walls, and foundations. During embankment or fill construction the geochemical action, with its resultant swelling in the process of compaction, is necessarily accompanied by the development of internal pres-

FIG. 2.—EQUIPMENT SETUP FOR PERMEABILITY TESTS, SWANZY RESERVOIR, IN CALIFORNIA, 1930

sures. At any given level, these pressures probably exceed the pressure imposed by the load, although there will be a gradual reduction as the material consolidates. The water applied in sprinkling the material for Gordon Valley Dam, carrying its original impurities and absorbing others, was taken up by the mass partly to become the hydration water of clayey material and partly to be evaporated. The completed structure presents an exceptionally dense, stable mass with no noticeable settlement after twenty-five years.

PERMEABILITY

Evidence of natural cementation of rock and rock material is common, resulting from induration due to atmospheric weathering, as well as from

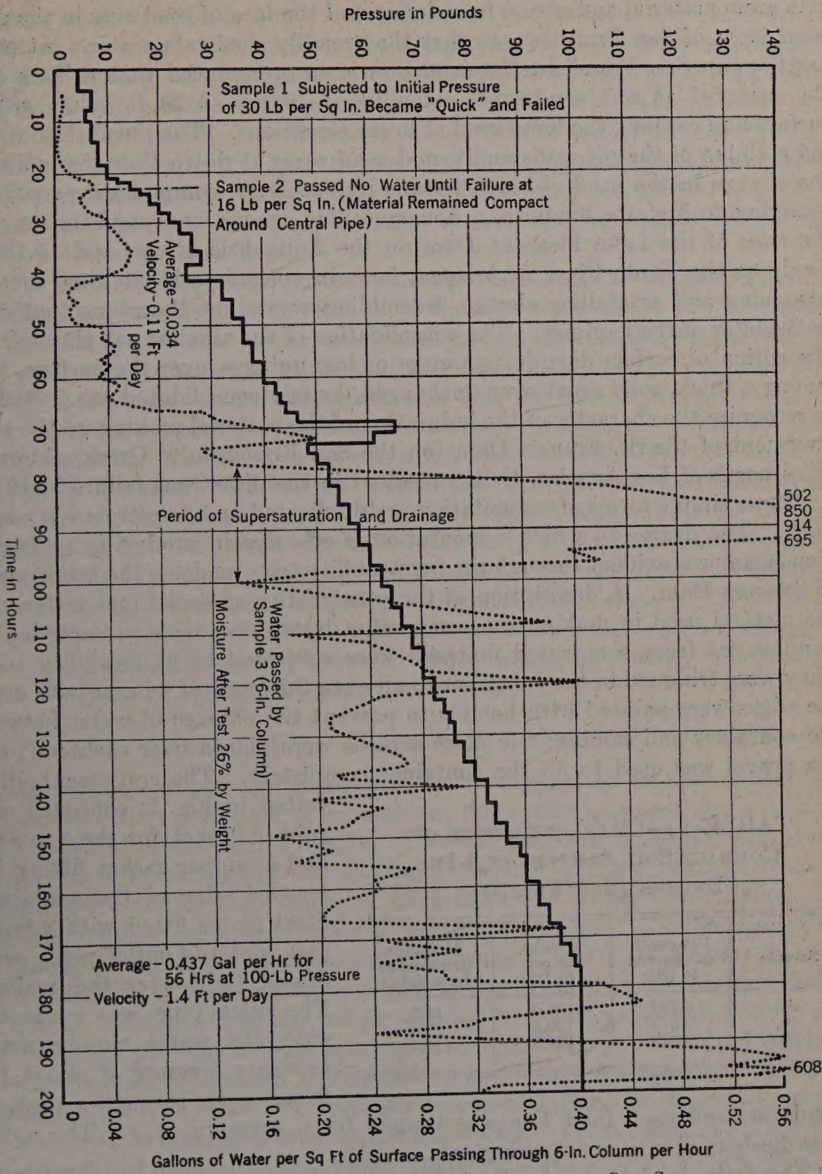

FIG. 3.—PRELIMINARY PERMEABILITY TESTS ON COMPACT SOIL SAMPLES (4-IN. LAYERS) SWANZY DAM, IN CALIFORNIA, 1930

injection of cementing material. Inspection of dam sites in sedimentary formations has revealed outcrops subjected to shell hardening[6] as a natural consequence of the oxidation, hydration, and secondary deposition of iron minerals cementing the grains and filling the interstices of the rock surfaces.

[6] *Bulletin No. 26*, California Dept. of Public Works, Div. of Water Resources, Sacramento, Calif., 1930, p. 511.

The same material and action have indurated the face of road cuts in the dune sand areas of San Francisco, so that they readily shed rain water. At many locations in San Francisco the condition is so pronounced that drillers class the material as soft sandstone, extending as much as 20 ft below ground surface and capping the loose sand at lower elevations. The purplish to rusty-red staining of the pit walls and tested sand cores at Sutro Forest was due to the change in the sand of black ferrous iron to ferric compounds, eventually changing to hydrate limonite, a noncrystalline concretionary substance. At the sites of the Lake Pleasant Dam on the Aqua Fria River, and at Camp Verde on the Verde River in Arizona, faces in volcanic ash exhibited marked hardening and crystalline change, resembling crystalline limestone that rang to the blow of the hammer. The consolidation of the alkaline ash through the absorption of carbon dioxide was more or less uniform over the surface, producing a thick, solid crust over unchanged, loosely consolidated ash. Failure to recognize the character of the induration of the material making up the west abutment of the St. Francis Dam (on the San Francisquito Creek, about 40 miles north of Los Angeles, Calif.) resulted in the disastrous failure in 1928.[7]

These simple forms of cementation are duplicated and accelerated in earthwork. The degree to which cementation is effective in producing an imprevious mass was evident through the permeability tests made on the test samples at Swanzy Dam. A description of the construction material and water, and the method used in making the compaction tests, have been presented. All samples cut from compacted material were subjected to permeability tests. They were trimmed in the container to an even thickness of 6 in. at both ends; the edges were painted with hot tar to prevent the passage of water between the container and sample; fine mesh screens were placed over each end; and pea gravel was used to fill the container completely. The equipment, illustrated in Fig. 2, consisted of a rubber gasket for the top edge and a copper gasket fitting the beveled edge of the container. Steel plates fitted with 8 bolts, and inlet and outlet pipes, were drawn tight over the gaskets. The inlet pipe was connected with the water supply main, having a pressure of about 140 lb per sq in. through a pressure regulator, and each inlet line was tapped for a pressure gage. The outlet pipe discharged into a measuring can.

TABLE 8.—Characteristics of Compact Soil Samples in 4-In. Layers (See Fig. 3)

Sample	1-ft depth compacted to (ft):	Weight (lb per cu ft)	Moisture (percentage by weight)
1	0.735	108.0	15.7
2	0.675	120.5	17.6
3	0.638	127.5	20.5

The tests were made simultaneously on 2 samples. The test results are stated in Table 8 and are shown graphically in Fig. 3. Sample 1 was compacted with sea water. The water was turned in at 30 lb per sq in. and all the fine material was washed from the container into the can immediately, there being no effective bond between grains. Sample 2 was the first compacted with soil water from the test pit. It remained consolidated until subjected to a

[7] *Western Construction News*, April 10, 1928, p. 234.

pressure of 16 lb when a "pipe" developed between the inlet and outlet in the center of the sample. A solid plate was inserted below the inlet on sample 3; and that sample, as well as subsequent samples, was allowed to stand with water at a 4-lb pressure for 24 hours before pressures were built up. The permeability of the sample is expressed in rate of flow in gallons per hour through a 6-in. column over 1 sq ft of its cross section, with a vertical path of percolation under increasing heads. The temperature of the water was constant at 55° F. The results obtained with sample 3 were typical, and represented an average of those tested subsequently.

The tests indicated that, for the heads that would prevail behind a structure completed to heights of from 60 ft to 70 ft, a soil mass would be consolidated by the cementation that accompanies working, and the compact structure of the soil and its impermeability would thus be maintained. The recommendation, based on the tests and investigations, was that the dam be designed without a paved facing or other provision against seepage through the structure. That recommendation was found to be warranted when, after the reservoir had been placed in operation, test borings were made through the embankment and no water was encountered above foundation rock. Similar tests for the permeability of the compacted clay core material in a proposed gravel embankment (Table 7, sample 5) showed that practical impermeability was achieved through the regeneration of abundant carbonates in the material, 20% soluble in a 5% solution of hydrochloric acid. Under these conditions, a thickness of 2 ft, pneumatically tamped between forms, would be entirely adequate to serve the purpose at a considerable saving in cost.

Conclusion

These observations and comments are not presented as criticism of test and construction procedure in general use, but rather as suggesting a broader base for the interpretation of results. Personal, practical experience has proved that, with a knowledge of the mineralogical and chemical characteristics of natural soils, and of their behavior when disturbed during construction, it is possible to utilize those materials with safety and economy. An understanding of the geochemical reactions resulted in a saving in cost of the Swanzy Dam by the elimination of the impervious core or facing planned in the original design. It is believed that economies can be effected in many ways, and failures can be prevented through a consideration of the geochemical action and reaction that are certain to occur in all engineering use of natural materials. From a geological point of view the processes (reconsolidation, for example) cannot be dealt with as invariable laws, but as tendencies. Local variations of mineral constituents of both earth and water create variation in the product, which is the union of elements from several sources—the earth, the air, and the water. It is neither possible nor necessary, to determine mathematical proportions readily, but it is important to recognize the facts and to be guided accordingly in construction. The observations and tests cited in reference to earthwork were the result of the application of elementary principles of geologic processes.